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IMPROVED HIGH STRENGTH ARMOR STEEL THROUGH TEXTURING

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METALS RESEARCH DIVISION

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ABSTRACT

The mechanical and ballistic properties of a high hardness armor material specially processed to develop an increasing (112)+(111) type texture has been established. Results indicate that the ballistic properties of textured armor, 0.50" nominal thickness, is substantially higher than that of uncontrolled or random textured armor of equal hardness at all obliquities tested up to 45 degrees against the cal. .50 AP M2 ammunition. The effect of texture on critical material characteristics such as fatigue, impact energy, fracture toughness, transition temperature, and uniaxial tension were determined. Mechanical property enhancement was developed by texturing. Textured material displayed increased strength, stiffness, fracture toughness, and lower transition temperature. Improved fatigue life with specimen orientation was established. Various notch orientations were examined. Face-notched specimens were up to fifty percent superior in toughness compared to identical edge-notched material. Results indicate that since most engineering design applications involve a single critical property in one principal direction it should be possible to take advantage of anisotropic mill products to produce more efficient and reliable vehicles and structures.

0.5 in.

CONTENTS

INTRODUCTION

During metal manufacturing processing, such as rolling of sheet and plate, the polycrystalline aggregate of the material acquires a crystallographic preferred orientation or texture. Textures develop because metals are crystalline and all crystals are anisotropic with respect to some of their properties. A schematic representation of the extreme conditions is illustrated in Figure 1. A metal having a random texture, nonpreferential alignment of the crystallites, would display no variation of properties with testing direction. This material is shown in Figure 1a and is considered to be isotropic. However, with proper processing the random material can acquire a preferred orientation as in Figure 1b. The behavior of this metal will be anisotropic, the properties varying from one direction to another. There are two principal types of material properties variation in textured materials, referred to as planar and normal anisotropy. With planar anisotropic materials the properties vary in the plane of the plate, whereas normal anisotropic materials exhibit different properties through the thickness from those in the plane.

The development and control of textures is extremely important for it provides a method to optimize desired mechanical-physical design properties in a given direction for various metals. Although recent studies have shown that texture can dramatically affect the properties of titanium[1,2] and could be utilized

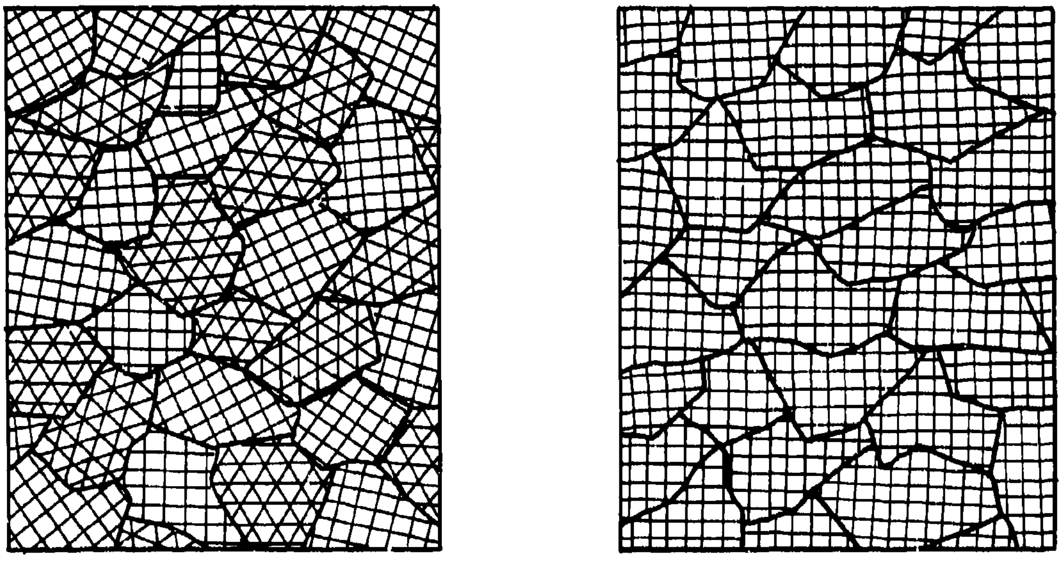


Figure 1. Schematic representation of a metal having irregular grain boundaries with (a) random and (b) preferred orientation.

1. LARSON, F. R., and ZARKADES, A. *Textured Titanium Technology* in Advances in Deformation Processing, Plenum Publishing Corp., New York, 1978.
2. LARSON, F. R., and ZARKADES, A. *Properties of Textured Titanium Alloys.* Metals and Ceramics Information Center, Battelle Columbus Laboratories, Report MCIC-74-20, June 1974 (AD 781 884).

as a third dimension to alloy development, along with composition and microstructure, the most successful industrial applications continue to be in the improvement of drawability[3] and magnetization of steel.[4]

With increasing pressure to use our resources efficiently, the possibility of improved material characteristics via texturing becomes of significant importance. The development of higher strength and/or ballistic-resistant material is a continuing DoD need, and would result in not only better protection but in improved vehicle mobility and increased pay load possibilities. The search for higher strength/ballistic-resistant material has usually resulted in increased cost for new alloys and/or processing necessary to obtain the upgrading of performance or increased vehicle weight. However, texturing has provided a new answer to this ever-increasing need for better ballistic performance with no price-weight penalty, and coincident improved mechanical properties. This potential breakthrough is a result of the transfer of technology and cooperative effort between government and private industry.

Deformation of austenite and increased strength of the quenched martensite has been documented by previous investigators including Kula and Dhosi who observed that thermomechanical processing can result in a textured material.[5,6] Through programs funded at the United States Steel Corporation Research Laboratory, processing parameters have been established which result in specific reproducible texture orientations in armor-type steel.[7-9] The influence and effect of texture formed from quenched deformed austenite on the mechanical properties has been separated from other metallurgical parameters co-existing with texture.[8] The textured armor steel exhibits improved ballistic resistance to conventionally uncontrolled rolled steels of equal hardness at normal obliquity. This superior ballistic resistance has been rationalized through a detailed theoretical study of texture strengthening conducted under contract at Rockwell International Science Center.[10] In concert with these studies the effect of texture on the ballistic performance at various obliquities and the delineation of the importance of texturing on the optimization of other critical properties were determined at AMMRC and are the subjects of this paper.

3. WHITELEY, R. L. *The Importance of Directionality in Drawing Quality Sheet Steel.* Trans. ASM, v. 52, 1960, p. 154-169.
4. GRAHAM, C. D., Jr. *Textured Magnetic Materials.* General Electric Company, TIS 64-RL-3752M, 1964.
5. KULA, E. B., and DHOSI, J. M. *Effect of Deformation Prior to Transformation on the Mechanical Properties of 4340 Steel.* Trans. ASM, v. 52, 1960, p. 321-345.
6. KULA, E. B., and LOPATA, S. L. *Preferred Orientation in Warm-Worked and Heat-Treated 4340 Steel.* Army Materials and Mechanics Research Center, WAL TR 830/10, October 1958.
7. SPEICH, G. R., HU, H., and MILLER, R. L. *Effect of Preferred Orientation and Related Metallurgical Parameters on Mechanical Properties and Ballistic Performance of High-Hardness Steel Armor.* United States Steel Corp., Contract DAAG46-73-0244, Final Report, AMMRC CTR 74-39, May 1974.
8. HU, H., SPEICH, G. R., and MILLER, R. L. *Effect of Crystallographic Texture, Retained Austenite and Austenite Grain Size on the Mechanical Ballistic Properties of Steel Armor Plates.* United States Steel Corp., Contract DAAG46-75-C-0094, Final Report, AMMRC CTR 76-22, July 1976.
9. HU, H. *Studies of Texture Development in Steel Armor Plate.* United States Steel Corp., Contract DAAG46-77-C-0014, Final Report, AMMRC CTR 77-19, July 1977.
10. GHOSH, A. K., and PATON, N. E. *Deformation of Textured Steels.* Rockwell International Corporation Science Center, Contract DAAG46-77-C-0054, Final Report, AMMRC TR 78-40, September 1978.

MATERIAL

A number of 0.50-inch-thick armor plates having $(112)[1\bar{1}0]+(111)[\bar{1}\bar{1}2]$ texture of various intensities were produced under contract at United States Steel.[9] The material was processed from 500-pound heats having the nominal chemical composition shown in Figure 2 and rolled 60 to 90 percent isothermally at 1500 F, water quenched and tempered at 350 F for 1 hour. All material conditions had a hardness ranging from 55.2 to 56.0 HRC. The microstructure for the plates was determined to be banded martensite as previously reported.[9]

Crystallographic preferred orientation was determined for the (110) plane utilizing the X-ray diffraction reflection technique.[9] Pole figures of subject material are illustrated in Figure 3. They were determined utilizing MoK_{α} radiation and are plotted out to a tilt angle of 80 degrees. Increasing maximum intensity (I) of the (112)+(111) texture is evident with rolling reduction from I=3.75 at 60 percent reduction to I=9.05 at 90 percent.

BALLISTIC PERFORMANCE

The resistance to penetration of the textured armor was determined by conducting a protection ballistic limit, (PBL V_{50}) test at obliquities from 0 to 45 degrees. This measures the critical velocity at which the armor target has a 50 percent probability of penetration, with penetration occurring whenever armor or projectile fragments pierce a 0.020-inch-thick 2024-T351 Al witness plate located six inches behind and parallel to the armor.[11]

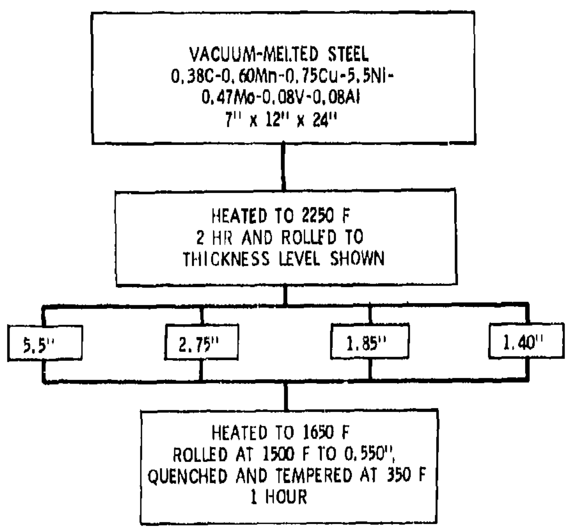


Figure 2. Chemical composition and processing procedure for improved steel armor.

11. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor - 1979 (U).* Army Materials and Mechanics Research Center, AMMRC TR 79-10, February 1979 (Confidential Report).

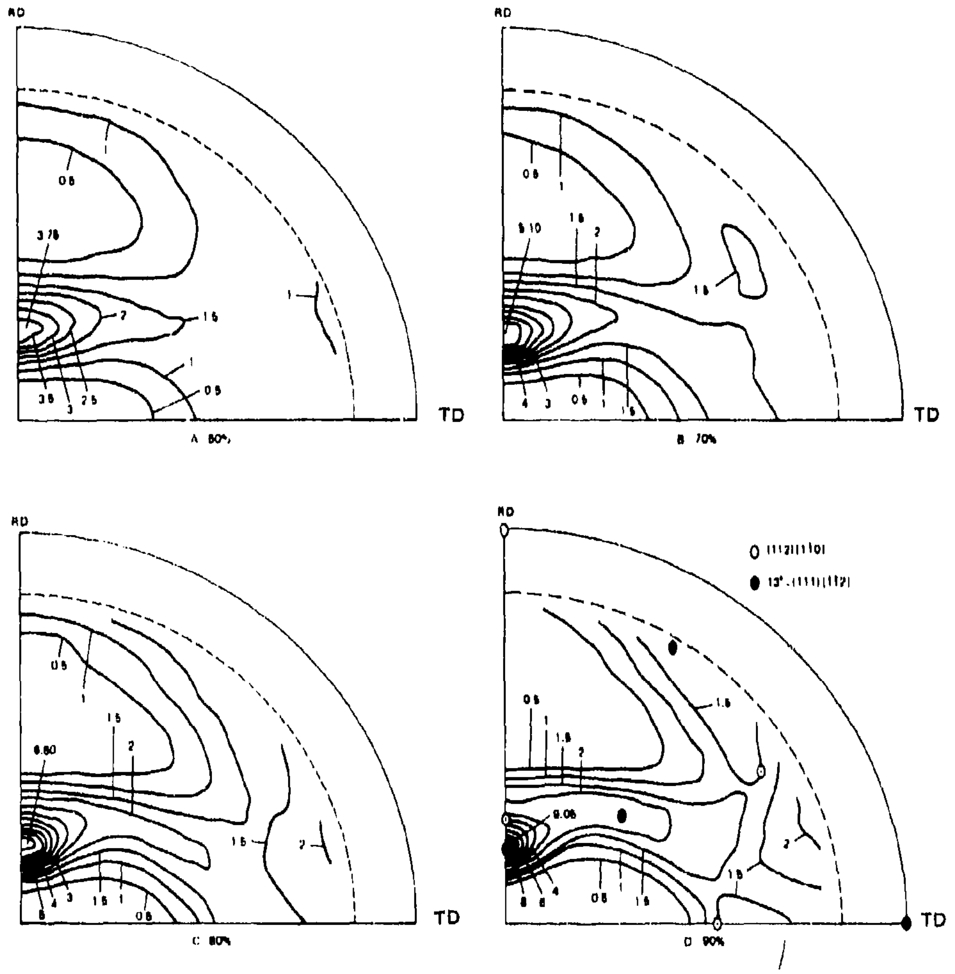


Figure 3. (110) Pole figures of the plates rolled to various reductions at 1500 F, then quenched and tempered (Ref. 9).

The effect of increasing texture intensity of the (112)+(111) type is clearly indicated by the V_{50} results for 0 degree obliquity against caliber .50 AP M2 projectiles as shown in Figure 4.[9] A 25 percent improvement in ballistic limit is displayed by the textured armor, I=9.1, at zero degree obliquity over random textured material of equal hardness. As observed by Abbott,* the armor tested at normal incidence had a standard deviation σ of approximately 30 feet per second. This indicates the material to be of "uniform good quality". Ballistic data subjected to statistical analysis at Aberdeen Proving Ground show a similar scatter band[12] for homogeneous steel armor tested against the caliber .50 AP M2 at zero degrees.

*ABBOTT, K. H., Army Materials and Mechanics Research Center, DF, 18 March 1977.

12. KELTON, J. C. *Acceptance Tests of Armor - Statistical Survey of Ballistic Data for Specification and Design Requirements (U).* Aberdeen Proving Ground, APG DPS 1951, March 1966.

A plot of the effect of obliquity, other than zero, on the ballistic limit is shown in Figure 5. Results indicate increasing ballistic resistance with increasing texture intensity, I≈4 to 9 at obliquities of 15, 30, and 45 degrees against the caliber .50 AP M2 projectile. Important here, also, is that the data obtained are within normally accepted scatter bands for good quality armor. To obtain ballistic results for the isotropic condition I≈1.0, plates having an I=3.8 were

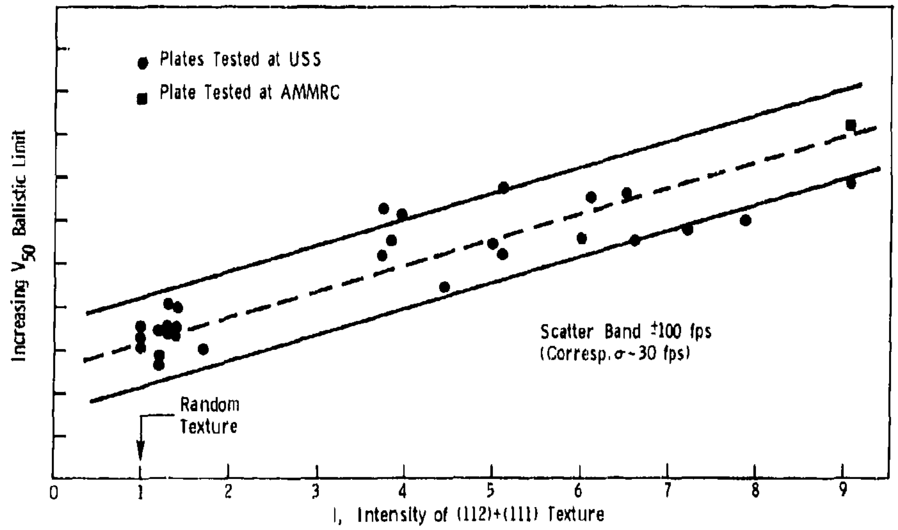


Figure 4. Correlation of caliber .50 AP M2 ballistic limits with texture intensity, zero degrees obliquity (Ref. 9).

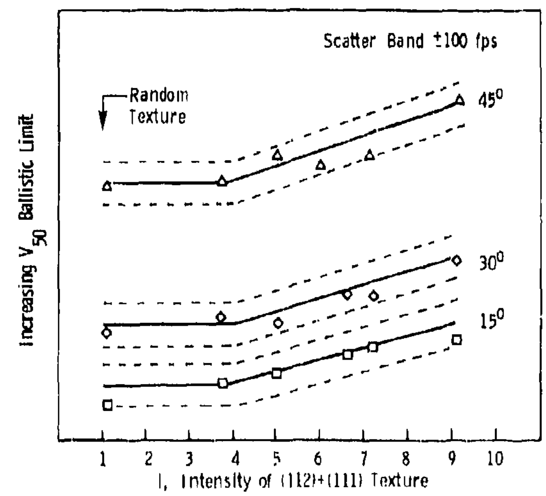


Figure 5. Protection provided by steel armor with increasing texture intensity against caliber .50 AP M2 projectiles at various obliquities.

randomized by reaustenitizing at 1800 F for one hour and tempering at 350 F. The results indicated in Figure 5 show that no effect of texture, at other than normal incidence, is apparent between texture intensity 1 to 4.

The ratio of areal density of standard rolled homogeneous steel armor to the areal density of experimental armor with the same penetration resistance is commonly referred to as the weight merit ratio. This parameter also showed a significant increase with increasing texture intensity. The textured armor, I≈9.0, in fact, had a rating which was over 40 percent better than the isotropic material at equivalent hardnesses.

Results from previous investigations have indicated that with increasing intensity of the (112)+(111) type texture a coinciding propensity for backspall occurs.[8,9] Although a complete understanding of this failure phenomenon is not available, backspall can be a result of the increased velocity with accompanying higher tension and compression waves and/or related to the inherent microstructural features of the heavily rolled material. The tendency of armor to backspall can be evaluated by testing with a chisel-shaped nose projectile as outlined in MIL-P-46593. Textured material was examined against the fragment-simulating projectile (FSP) and the cursory results are shown in Figure 6. Although backspall was evident, the protection limit established at zero degree obliquity against the 20-mm FSP (830-grain) projectile compares favorably to steel armor of similar hardness.

MECHANICAL PROPERTIES

The fact that texture can influence the anisotropy of mechanical properties has been documented by theoretical plasticity procedures established by previous

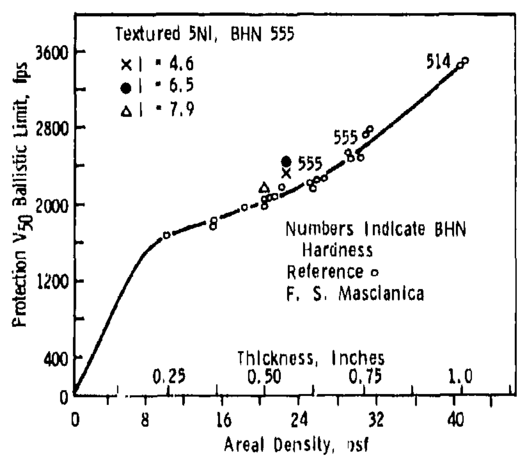


Figure 6. Protection provided by steel against 20-mm (830-GR) fragment-simulating projectiles at zero obliquity.

workers, including Hosford and Backofen[13] utilizing the crystallographic analysis of Taylor.[14] With the calculations of M Taylor factors, ratio of yield strength to critical resolved shear stress over the full stereographic triangle, as shown in Figure 7, the strength of a random polycrystalline aggregate is calculated to be 3.06. The relative strength anisotropy of wire having a fiber texture, or plate material having a texture symmetric about the plate normal, can also be predicted. For example, a [111] fiber-textured steel wire should be 20 percent stronger than random material and 50 percent stronger than one with a [100] texture. Correspondingly, the modulus of elasticity has been shown to be very anisotropic for most cubic-structured alloys. The cube diagonal [111] is the direction of maximum stiffness at 42.7×10^6 psi with the [100] cube edge being the lowest at 18.0×10^6 psi. Further examples of the anisotropic characteristics of varied properties are shown in Table 1 for the cubic structure.[15]

In general, most strength specifications for flat steel mill products prescribe the transverse specimen for test qualification. However, it should be of importance to both consumer and producer alike to understand the effect of orientation on the mechanical properties. This is especially true for conditions where in the final product the maximum applied stress does not coincide with that specified test direction. The tension properties of armor steel as a function of increasing texture intensity were determined in three orientations, longitudinal (L), transverse (T), and 45 degrees to the rolling direction (see Table 2).

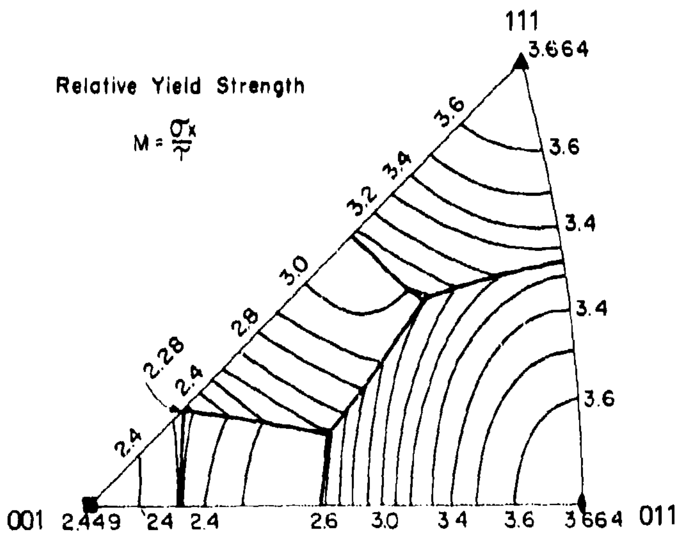


Figure 7. Orientation dependence of M for axially symmetric flow (Ref. 12).

13. HOSFORD, W. F., and BACKOFEN, W. A. *Strength and Plasticity of Textured Metals* in Fundamentals of Deformation Processing, Syracuse University Press, New York, 1964, p. 259.
14. TAYLOR, G. I. *Plastic Strain in Metals.* J. Inst. Metals, v. 62, 1938, p. 307-324.
15. CHIN, G. Y. *Textured Structures.* ASM Metals Handbook, v. 8, 1973, p. 229-232.

Table 1. Examples of Dependence of Mechanical and Physical Properties on Crystal Direction (Ref. 15)

Property(a)	Example: Metal	Crystal direction	Value of property
Young's modulus	Copper	<111>	193,000 MPa (28,000,000 psi)
		<100>	69,000 MPa (10,000,000 psi)
Yield strength	Magnesium	*c*-axis 5° from tensile axis	10 MPa (1450 psi)
		c-axis 45° from tensile axis	1.7 MPa (246 psi)
Thermal expansion ..	Uranium	*a*-axis	33×10^{-6}/K (59.4×10^{-6}/F)
		b-axis	-6.5×10^{-6}/K (-11.7×10^{-6}/F)
Electrical resistivity ..	Tellurium	*c*-axis	6×10^{-4} Ωm (60,000 microhm-cm)
		90° from *c*-axis	15×10^{-4} Ωm (150,000 microhm-cm)
Magnetic-flux density.	Cobalt	*c*-axis	1.8 T (18,000 gausses) (b)
		90° from *c*-axis	0.6 T (6,000 gausses) (b)

(a) The following properties are anisotropic for cubic metals: compressibility and bulk modulus, Young's modulus, Poisson's ratio, yield strength, tensile strength, elongation, coefficient of friction, magnetic-flux density (below saturation), magnetic permeability, magnetostriction. The following properties are isotropic for cubic metals: coefficient of thermal expansion, thermal conductivity, electrical resistivity, dielectric constant, Thomson coefficient, Peltier coefficient, index of refraction. (b) At a magnetic field strength of 1.6×10^5 A/m (2016 oersteds).

Table 2. MECHANICAL PROPERTIES OF 5Ni STEEL ARMOR

Texture Intensity, I_{max}	Yield Strength, 0.2% Offset, ksi			Ultimate Tensile Strength, ksi			Modulus, psi × 10^6			Elongation, %			Reduction of Area, %		
	L	45°	T	L	45°	T	L	45°	T	L	45°	T	L	45°	T
1.3	220	-	223	299	-	299	28.1	-	28.3	15.0	-	15.0	48.6	-	38.6
3.8	235	238	240	311	309	316	28.9	29.4	32.8	13.1	12.0	8.5	44.0	42.0	24.0
6.6	237	233	250	303	310	317	32.0	29.5	33.2	13.1	12.2	9.5	46.0	39.1	28.8
7.9	232	237	248	298	302	313	30.1	32.3	33.3	13.9	12.7	10.2	47.9	39.0	32.7
9.1	235	242	254	305	305	316	29.9	32.4	32.9	11.0	11.5	9.0	43.7	36.2	30.8

A round tension specimen of 0.252-inch diameter was utilized. Examination of the nearly random condition, I=1.3, reveals the isotropic condition of the material strength characteristics with no planar anisotropy. With increasing texture intensity, however, an increasing longitudinal to transverse yield strength differential is oberved: 3 ksi at I=1.3, 5 ksi at I=3.8, 13 ksi at I=6.6, 16 ksi at I=7.9, and 19 ksi at I=9.1. Comparison of the highly textured material yield strengths obtained in the transverse direction to the random condition indicates a marked increase in strengths obtained with texturing. Both the ultimate tensile strength and Young's modulus results showed some degree of planar anisotropy with the maximum values occurring in the transverse direction for the textured conditions.

CHARPY IMPACT AND TRANSITION TEMPERATURE

It has been established that cleavage is crystallographic in nature and in iron occurs on the (100) plane.[16] Consequently, the preferential alignment of this component via texturing can affect the anisotropy of toughness. For example, a weakening of the (100) in the rolling plane of steel plate will result in material with improved cleavage resistance through the thickness and also influence

16. SCHMID, E., and BOAS, W. *Plasticity of Crystals*, Hughes and Co., Ltd., London, 1950.

the transition temperature.[17,18] Impact energy anisotropy has also been found to be related to texturing in other materials including titanium[19] through plastic-flow anisotropy.

In this study, standard 0.394"-square impact specimens were machined from plates having the (112)+(111) texture with little (100) orientation in the plane of the plate. As illustrated in Figure 8, specimen orientations were longitudinal (L-T), transverse (T-L), or 45° (LT-LT) to the rolling direction with the standard edge-notch orientation. However, to establish if there was any effect of notch orientation for the highly textured material, I=9.1, specimens were notched parallel to the plate surface or face notched (L-S), (T-S), and (LT-S). Specimens were tested on a 217 ft-lb capacity pendulum-type machine with a striking velocity of 17 ft/sec.

The Charpy transition temperature, the lowest temperature at which 100 percent fibrosity still exists, was determined for each orientation and texture intensity by breaking a series of specimens over a range of temperatures. At high temperatures the specimens broke with ductile fibrous-type fracture and absorbed higher energy. As the temperature was lowered the energy level decreased and a change in the fracture appearance was noted, resulting in what is called the ductile-to-brittle transition. A typical curve is illustrated in Figure 9 for the highly textured material, I=9.1. The effect of texture intensity on the transition temperature for all material examined is shown in Figure 10. Results have been established that while specimen and notch orientation have no effect on transition temperature, texture intensity of the (112)+(111) type has a marked effect

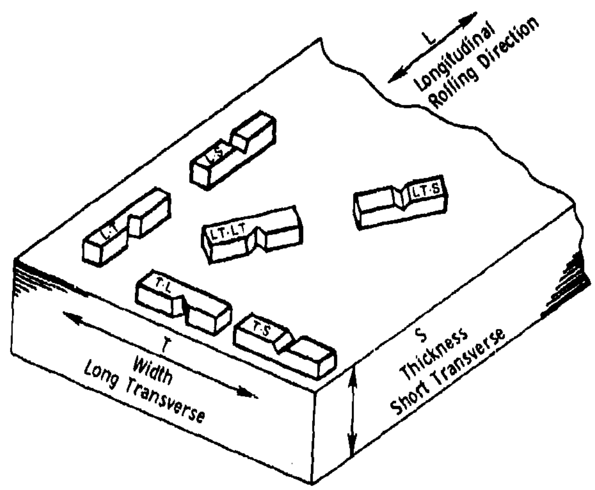


Figure 8. Charpy specimen - notch orientation.

17. BRAMFIT, B. L., and MARDER, A. R. *The Influence of Microstructure and Crystallographic Texture on the Strength and Notch Toughness of a Low-Carbon Steel* in Processing and Properties of Low Carbon Steel, Met. Soc. of AIME, 1973, p. 191.
18. KANEHO, T., and TEROSOKI, F. *Effect of Texture on the Toughness of Pure Iron.* Trans. ISIJ, v. 15, 1975.
19. ZARKADES, A., and LARSON, F. R. *Effect of Texture on the Charpy Impact Energy of Some Titanium Alloy Plate.* Army Materials and Mechanics Research Center, AMMRC TR 72-21, June 1972.

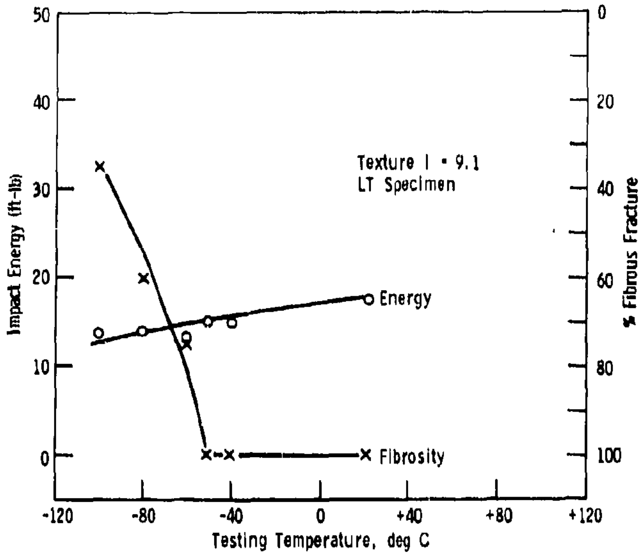


Figure 9. Transition curve for textured steel armor.

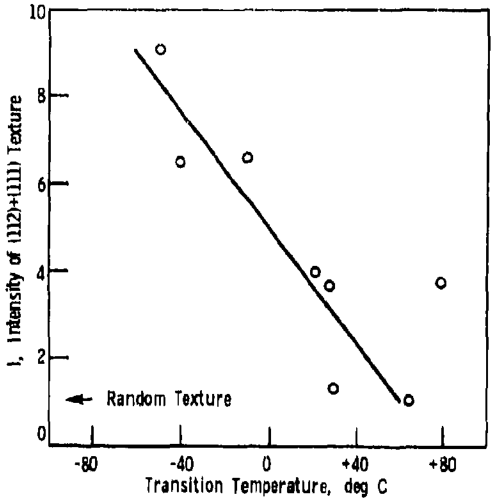


Figure 10. Effect of texture intensity on the transition temperature of armor steel.

The effect of specimen and notch orientations on the Charpy impact energy of the highly textured plate material is shown in Table 3 for two test temperatures. Immediately evident is the marked superiority of the face-notched specimens with the crack propagating in the thickness direction, over the edge-notched samples in both the longitudinal and 45-degree orientations. The room-temperature longitudinal face-notched specimen, in fact, has approximately 50 percent higher energy absorption than the edge-notched specimen. For all material texture intensities, specimen and notch orientations it was established that the longitudinal orientation was superior.

Table 3. EFFECT OF SPECIMEN NOTCH ORIENTATIONS ON THE TOUGHNESS OF TEXTURED ARMOR I=9.1

Specimen Notch Orientations		Impact Energy, ft-lb, at -40 C	+22 C
Edge-Notched -	L-T	14.9	17.5
	45°	13.9	15.2
	T-L	11.1	11.1
Face-Notched -	L-S	19.4	26.2
	45°	15.8	17.5
	T-S	10.0	11.2

Fibering, which is noncrystallographic in nature and results in anisotropy via inclusions, porosity, and elongated grain structure, was qualitatively ruled out as the cause of this impact anisotropy. Delaminations of the fractured Charpy specimens, associated with fracturing anisotropy and brought about by mechanical fibering were not found in the magnitude described by English.[20] Also, there was no difference in impact strength for specimens in the TS and TL orientations normally attained with a fibered or elongated structure.

20. ENGLISH, A.J. *Influence of Mechanical Fibering on Anisotropy of Strength and Ductility.* Journal of Metals, April 1965, p. 395.

FRACTURE TOUGHNESS

In recent years fracture mechanics has brought about a better understanding of fracture toughness. However, the influence of texture on the fracture toughness, (K_{Ic}) plane-strain, has received very little attention from the technical community with the result that no clear understanding of the problem is available. It is a complex situation, for one must consider each preferred orientation with various specific specimen and notch orientations and the effect on strength and ductility.

To determine this important material characteristic of fracture toughness, Charpy specimens were tested from three orientations as previously indicated in Figure 8. Two notch orientations, edge-notched and face-notched, were examined for the highly textured material and isotropic conditions. The Charpy samples were precracked and loaded by three-point bending in a ManLabs Slow Bend Machine at a headspeed of 0.05 inch/minute. Results are shown in Figure 11. The superiority of up to 30 percent of the face-notched samples over the edge-notched condition is clearly apparent, with the 45° specimen orientation resulting in the highest fracture toughness. Data illustrated are for a single test with the exception of the highly textured condition, which is an average of two tests. The isotropic versus anisotropic behavior of material is clearly apparent and educe the improvement possible by proper texture-load carrying considerations. A comparison of the fracture toughness values of the textured material to those of electroslag remelted steel ESR 4340, as obtained by Anctil, et al,* is illustrated in Figure 12. The toughness of the textured material is superior at all specimen and notch orientations.

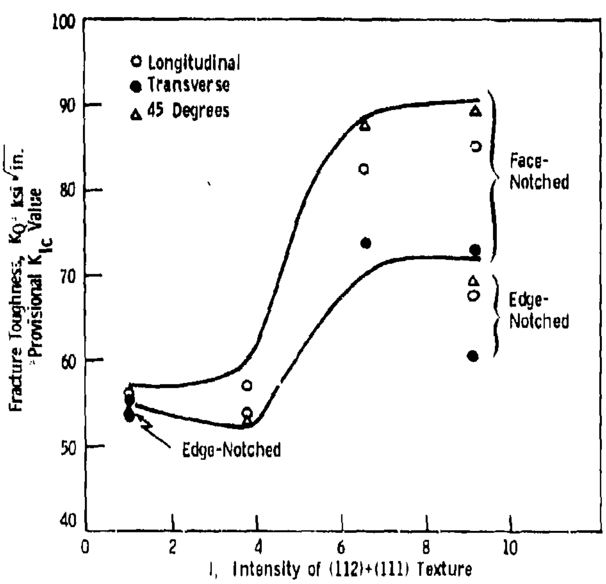


Figure 11. The effect of specimen and notch orientations, and texture intensity on the fracture toughness of armor steel.

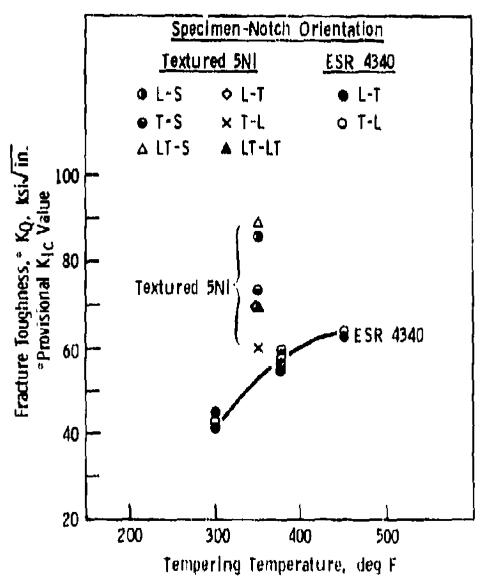


Figure 12. A comparison of fracture toughness properties.

*ANCTIL, A.A., DeSISTO, T.S., and KULA, E.B. *The Mechanical Properties of ESR 4340 Steel for Ballistically Critical Aircraft Components.* Army Materials and Mechanics Research Center (to be published).

FATIGUE

The variation of fatigue life with specimen orientation in textured materials has not been the subject of considerable effort. However, recent discoveries have indicated that large improvements in the fatigue life of hexagonal closed-packed titanium are possible and related to the influence of texture upon crack nucleation.[1] Thesis work conducted by Chandrathil[21] has illustrated fatigue anisotropy for face-centered cubic metals with a high degree of preferred orientation and suggests that body-centered cubic metals be examined.

To determine if texture can affect the fatigue life of high-strength, body-centered cubic steel, a limited number of hourglass-shaped specimens, shown in Figure 13, were machined from the longitudinal, transverse, and 45-degree orientation. Samples were tested at room temperature in tension-tension at a stress ratio of R=0.1 at 1800 rpm. Typical S-N curves were developed for the plate having a texture intensity of 7.9 at each orientation. These results are illustrated in Figure 14.

From Figure 15, which is a composite of the results, it is evident that large variations have been found for fatigue life in the high stress finite region and endurance limit. The diagonal or 45-degree specimen orientation has approximately a 1-1/2 log cycle superiority over the longitudinal orientation in the high stress region, with long cycle life at 85 percent of the yield strength. The material exhibited a ratio of 0.570 of the endurance limit to tensile strength at 45 degrees.

Another important aspect of these results is the high endurance limit, 170 ksi. A linear relationship often used for design purposes is endurance limit versus ultimate tensile strength. This is illustrated in Figure 16, for various strength

1. Dimensions in inches unless otherwise noted.
2. Dimensional tolerances fractional ±1/64 decimal ±0.001
3. Diameters D_1, D_2, and J concentric with $\boxed{A}$ 0.001 TIR.

Type	A	B	C	D_1	D_2	E	F	J	R_1	R_2
F 1	3-1/2	1-1/2	1.000	0.200	0.250	3/16	1	1/2-16-2A	1/4	5.000

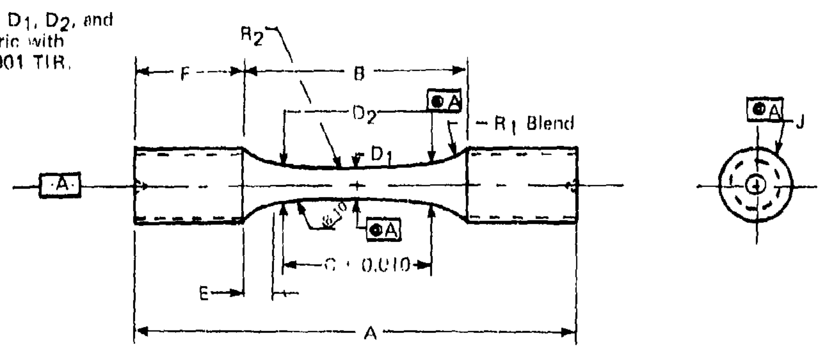
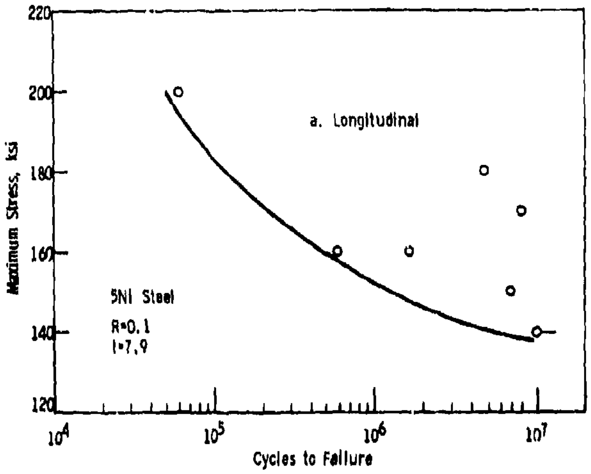
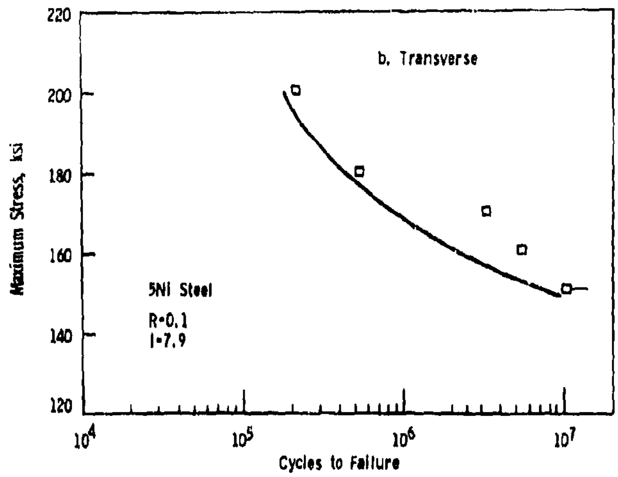


Figure 13. Fatigue specimen geometry.

21 CHANDRATHIL, N. *The Fatigue of Textured Face-Centered-Cubic Sheet Metals.* University of Saskatchewan, Ph.D. Thesis, 1968.





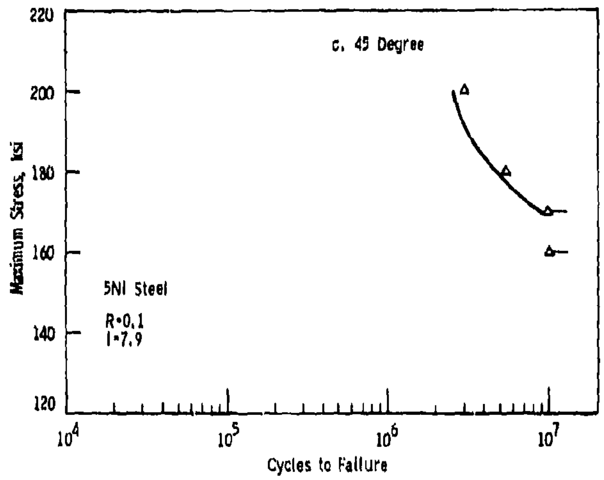


Figure 14. Fatigue life of textured armor specimens.

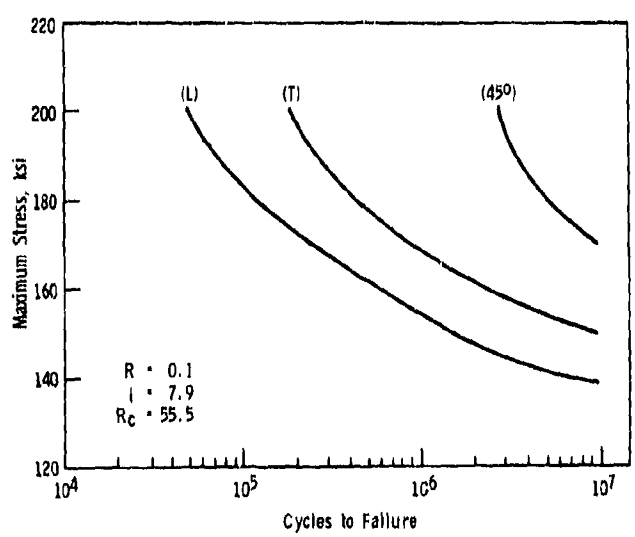


Figure 15. Effect of specimen orientation on the fatigue life of textured armor steel.

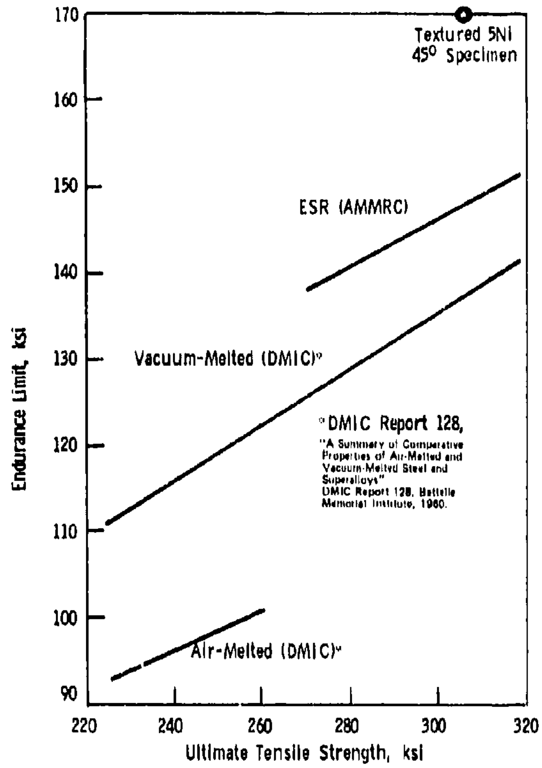


Figure 16. Comparison of endurance limits of 4340 and textured steel armor.

levels of 4340[22] compared to results obtained in the textured steel at 45 degrees to the rolling direction. The improvement illustrated is based on a limited number of tests and mandates the need for more texture studies. However, since most engineering design applications involve a single critical property, such as fatigue, in one principal orientation, it should be possible to take advantage of the anisotropic mill product.

SUMMARY AND CONCLUSIONS

Ballistic examination of a 0.50"-thick high-hardness steel armor specially processed to develop a (112)+(111) type texture against a caliber .50 AP M2 ammunition, at all obliquities, from 0 to 45 degrees, has established that the ballistic limit of the armor increased with increasing texture intensity I≈4.0 to 9.0. Results indicate up to 25 percent improvement in the ballistic penetration resistance of the textured, I≈9.0, over random textured condition at equal hardness. Continued ballistic examination of the 0.50"-thick material and armor with decreasing gage thickness is planned against various types of projectiles.

It was also found that crystallographic texture can affect many critical mechanical properties. Planar anisotropy in the textured steel was established for

22. AYVAZIAN, A. M., and PAPETTI, P. J. *Improved Homogeneous Steel Armor (U).* Army Materials and Mechanics Research Center, AMMRC SP 73-6, March 1973 (Confidential Report).

tensile properties, fatigue life, impact energy, and fracture toughness. In addition, it was ascertained that the notch orientation can significantly affect the fracture toughness and impact energy of the textured material. Face-notched specimens were up to 50 percent superior in toughness compared to edge-notched material.

Although no specimen or notch effect on the ductile to brittle transition temperature was noted, it was found that with increasing texture intensity a decrease in transition temperature occurs. Random textured material displayed a +60 C transition temperature compared to -60 C for the textured armor.

The substantial improvements in ballistic performance and mechanical properties illustrated is by no means the maximum limit of improvement attainable via texturing. With increasing knowledge and developing technological base, further improvements should be possible. The importance of producing better armor plate which will provide maximum protection of personnel or vital components for a minimum weight penalty is a primary goal; however, it should be realized that the technology base being built here could be easily transferred to other applications, where the optimization of mechanical properties can be attained via "tailor-made" textured material.

With proper selection and control of texture, increased structural efficiency and material conservation will result, because current design allowances reflect low material properties when unfavorable texture and specimen-notch orientations and/or random texture material exists.

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